REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01-03-2012	JOURNAL PAPER	Jun 2011 - Dec 2012

4. TITLE AND SUBTITLE
CloudSat Anomaly Recovery and Operational Lessons Learned

5a. CONTRACT NUMBER N/A

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Nayak, Michael; Witkowski, Mona; Vane, Deborah; Livermore, Thomas; Rokey, Mark; Barthuli, Marda; Gravseth, Ian; Pieper, Brian; Rodzinak, Aaron; Silva, Steve; Woznick, Paul

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Space Development and Test Directorate, Albuquerque, NM, 87117, USA
Jet Propulsion Laboratory – California Institute of Technology, Pasadena, CA, 91109, USA
Ball Aerospace and Technologies Corporation, Boulder, CO, 80301, USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Space Development and Test Directorate, Albuquerque, NM, 87117, USA

10. SPONSOR/MONITOR'S ACRONYM(S) SMC/AD

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited

13. SUPPLEMENTARY NOTES
Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This paper is also available on NTRS, the NASA Archive service.

14. ABSTRACT
In April 2011, NASA's pioneering cloud profiling radar satellite, CloudSat, experienced a battery anomaly that placed it into emergency mode and rendered it operations incapable. All initial attempts to recover the spacecraft failed as the resultant power limitations could not support even the lowest power mode. The team was able to execute a complex sequence of operations which recovered control, conducted an orbit lower maneuver, and returned the satellite to safe mode, within one 65 minute sunlit period. During the course of the anomaly recovery, the team developed several bold, innovative operational strategies. Details of the investigation into the root-cause and the multiple approaches to revive CloudSat are examined. Satellite communication and commanding during the anomaly are presented. A radical new system of "Daylight Only Ops" (DO-OP) was developed, which cycles the payload and subsystem components off in tune with earth eclipse entry and exit in order to maintain positive power and thermal profiles. The scientific methodology and operational results behind the graduated testing and ramp-up to DO-OP are analyzed. In November 2011, the CloudSat team successfully restored the vehicle to consistent operational collection of cloud radar data during sunlit portion

15. SUBJECT TERMS
CloudSat, NASA, satellite, constellation, formation flying, Guidance, Navigation, Control, Attitude Determination, Satellite Anomaly

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
(U)	(U)	(U)	UU	14	MICHAEL NAYAK / 808-891-7727

CloudSat Anomaly Recovery and Operational Lessons Learned

Michael Nayak[1]
Space Development and Test Directorate, Albuquerque, NM, 87117, USA

Mona Witkowski[2], Deborah Vane[3], Thomas Livermore[4] and Mark Rokey[5]
Jet Propulsion Laboratory – California Institute of Technology, Pasadena, CA, 91109, USA

and

Marda Barthuli[6], Ian J. Gravseth[7], Brian Pieper[8], Aaron Rodzinak[9], Steve Silva[10], Paul Woznick[11]
Ball Aerospace and Technologies Corporation, Boulder, CO, 80301, USA

In April 2011, NASA's pioneering cloud profiling radar satellite, CloudSat, experienced a battery anomaly that placed it into emergency mode and rendered it operations incapable. All initial attempts to recover the spacecraft failed as the resultant power limitations could not support even the lowest power mode. Originally part of a six-satellite constellation known as the "A-Train", CloudSat was unable to stay within its assigned control box, posing a threat to other A-Train satellites. CloudSat needed to exit the constellation, but with the tenuous power profile, conducting maneuvers was very risky. The team was able to execute a complex sequence of operations which recovered control, conducted an orbit lower maneuver, and returned the satellite to safe mode, within one 65 minute sunlit period. During the course of the anomaly recovery, the team developed several bold, innovative operational strategies. Details of the investigation into the root-cause and the multiple approaches to revive CloudSat are examined. Satellite communication and commanding during the anomaly are presented. A radical new system of "Daylight Only Operations" (DO-OP) was developed, which cycles the payload and subsystem components off in tune with earth eclipse entry and exit in order to maintain positive power and thermal profiles. The scientific methodology and operational results behind the graduated testing and ramp-up to DO-OP are analyzed. In November 2011, the CloudSat team successfully restored the vehicle to consistent operational collection of cloud radar data during sunlit portions of the orbit. Lessons learned throughout the six-month return-to-operations recovery effort are discussed and offered for application to other R&D satellites, in the context of on-orbit anomaly resolution efforts.

I. Introduction: CloudSat Mission

LAUNCHED in 2006 as part of the NASA Earth System Science Pathfinder (ESSP) program, CloudSat's unique millimeter-wavelength radar provides scientists valuable data on the vertical profiles of condensed

[1] Satellite Flight Test Engineer, Space Operations and Test Division, michael.nayak@kirtland.af.mil.
[2] CloudSat Flight Director, 4800 Oak Grove Dr.
[3] CloudSat Project Manager, 4800 Oak Grove Dr.
[4] Former Earth Science Mission Operations Chief Engineer, 4800 Oak Grove Dr.
[5] Former CloudSat Flight Director (Launch – Oct 2011), currently Senior Project Engineer, The Aerospace Corporation, 200 S. Los Robles Ave.
[6] System Engineer, Mission Systems Engineering, 1600 Commerce St.
[7] CloudSat ADCS Lead, Spacecraft Systems Engineering, 1600 Commerce St.
[8] Anomaly Lead & CloudSat Chief Engineer, Spacecraft Systems Engineering, 1600 Commerce St.
[9] Mission Ops Manager, Spacecraft Systems Engineering, 1600 Commerce St.
[10] Battery Consultant, SJS Consulting, Arvada, CO
[11] Former Mission Ops Manager, Program Execution, 1600 Commerce St.

water and ice that make up the structure of clouds. The scientific goal of the mission is to build the first global survey of the vertical structure of cloud systems and profiles of cloud liquid/ice water content. CloudSat was designed for a 22-month operational life and has just exceeded six years on-orbit, exemplifying both a robust system design and a very dedicated mission operations team.

Together with CALIPSO, a co-manifested launch partner and a NASA/CNES ESSP satellite, CloudSat joined the Afternoon Constellation or "A-Train" – an international series of Earth-observing satellites that follow nearly identical ground tracks and allow for near-simultaneous observations of the same terrain with a wide variety of complementary instruments. For example, CloudSat's ability to penetrate clouds with its Cloud Profiling Radar (CPR) is complementary to CALIPSO's LIDAR observations of aerosol interactions with clouds. The A-Train Constellation is in a near-circular, sun-synchronous polar orbit with equatorial crossings at a local mean time of 1:30 pm. At an altitude of about 705 km, the A-Train satellites enjoy almost 65 minutes of sunlight and 34 minutes of eclipse (subject to seasonal variation and orbit precession changes) per Earth revolution.

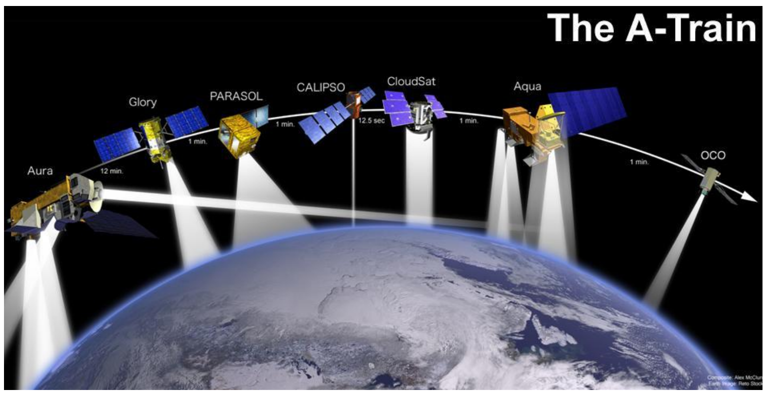

Figure 1. CloudSat's position in the Afternoon Constellation or A-Train[1].

Mission management, satellite control authority and risk decision authority are the responsibility of the CloudSat project office, located at the Jet Propulsion Laboratory (JPL), where the CPR was also designed, integrated and tested in partnership and with contributions from the Canadian Space Agency. Ball Aerospace & Technologies Corporation (BATC) designed and built the spacecraft bus, integrated and tested the space vehicle and is currently providing technical operations and anomaly resolution support. Through the worldwide Air Force Satellite Control Network (AFSCN), the US Air Force's Research, Development, Test and Evaluation (RDT&E) Support Complex (RSC) at Kirtland Air Force Base provides round-the-clock CloudSat operations, mission engineering and ground system sustainment.

II. CloudSat Provides International Science Value

Over a thousand times more sensitive than any ground-based weather radar, CloudSat's CPR has directly contributed to the improvement of global weather models, as well as our understanding of how Earth's clouds are affected by and influence climate change, filling a recognized and critical gap in the measurement and understanding of clouds for weather and climate research. The continuation of CloudSat observations is key in determining the variability of cloudiness on intra-seasonal to inter-annual time scales. This helps the global climate research community determine the relationships between the variability of clouds with precipitation and key environmental factors, establish important cloud-climate feedbacks and characterize changes on a decadal time scale. The unexpected loss of CloudSat data due to the battery anomaly of April 2011 (Section IV) had a significant influence on the evaluation and development of improved cloud schemes for weather and climate models, making its return to operations and the A-Train a high priority.

The rich synergy of A-Train observations has extended the usefulness of CloudSat observations and has enabled important advances. Fig 2 demonstrates how CloudSat, together with other A-Train instruments, provided the three-dimensional structure of cloud response to an El Nino event in February 2010. This figure shows tropical (5ºS-5ºN) averaged CloudSat cloud water content profiles in color shadings, Microwave Limb Sounder (MLS/A-Train) UT water vapor in color contours, Atmospheric Infrared Sounder (AIRS/A-Train) 500 hPa water vapor in the red curve, and NOAA sea surface temperature (SST) in the color map. The synergy of CloudSat with A-Train observations has provided our most definitive idea to date of how the atmosphere responds to El Nino climate variability.

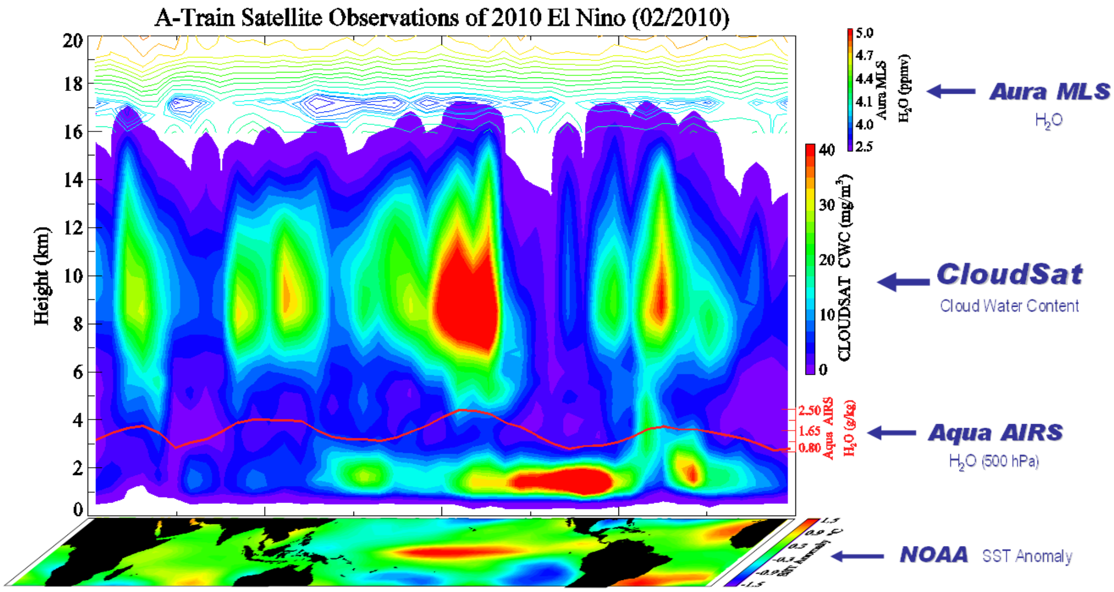

Figure 2. CloudSat contributes to observations of the response of the atmosphere to El Nino forcing[2].

However, observations of one or two such El Nino events are not sufficient to determine the range of response to climate variability. Multi-year datasets are required, as tropical-mean cloud anomalies are not linearly related to tropical-mean SST changes. As seen in Fig 3, during the CloudSat pre-anomaly operation period (2006-2011), two El Niños (2006-07 and 2009-10) exhibit nearly opposite tropical-mean cloud anomalies. Continued observations of cloud profiles by CloudSat, combined with the A-Train, are needed to quantify cloud response to climate variability, especially long-term cloud changes to the warming of surface temperature.

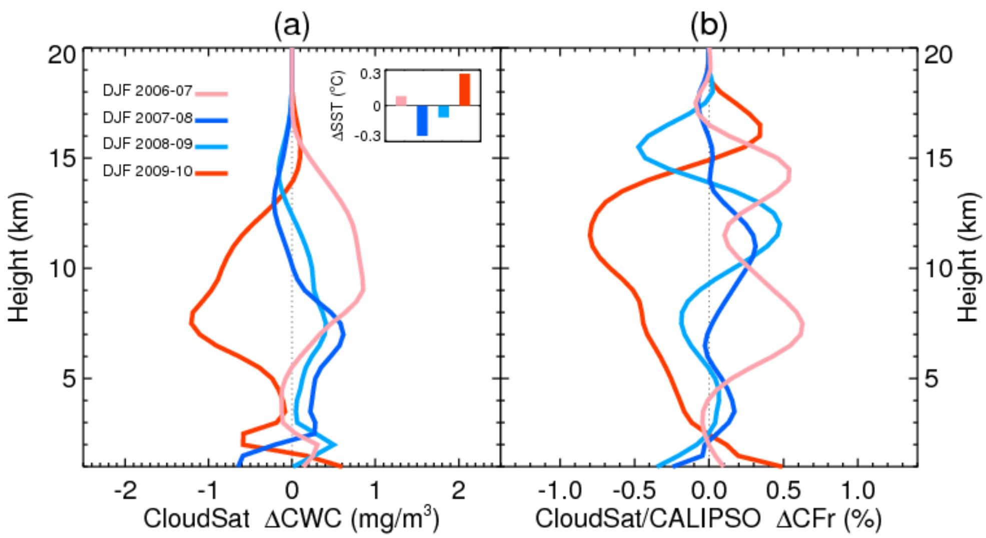

Figure 3. CloudSat cloud water content (CWC) and change in cloud fraction (ΔCFr) as a function of height in the atmosphere for two El Nino events (2006-20007 [pink] and 2009-2010 [red]) that exhibit nearly opposite tropical-mean cloud anomalies[2].

III. CloudSat Spacecraft System

The power, thermal, fault protection, and attitude control subsystems played key roles in the recovery from the April 2011 battery anomaly and the realization of the Daylight-Only Operations (DO-OP) mode. A brief overview of each is presented in this section.

A. Power Subsystem Overview

CloudSat uses a direct energy transfer power architecture, where two articulating solar arrays provide over 1,000 watts of solar power to recharge a 40 Amp-Hr battery. A Power Control Unit (PCU) regulates battery charge control and distributes power to spacecraft components over a hardwired essential power bus and four switchable power buses.[4]

B. Thermal Control Subsystem Overview

CloudSat's thermal subsystem is primarily passive, relying on multi-layer insulation and thermal radiators to control the temperature of the spacecraft, but also uses thermostatically and manually controlled heaters. Most heaters are used to prevent components from getting too cold in the safe modes, and can be enabled and disabled by ground command. However, several critical "survival" heaters are used to actively maintain components within tight temperature ranges, and by design, cannot be externally disabled.

C. Under-Voltage Fault Protection Overview

CloudSat has a variety of independent fault protection schemes. One of these schemes involves a series of under-voltage (UV) protection levels. As the battery discharges, the system voltage decreases; if discharged too far, the UV faults are sequentially tripped. The response to UV faults is to shed the power buses according to a hierarchical order to ensure that the more essential components such as the command subsystem and survival heaters continue to receive adequate power. The fault protection design proved very flexible, and the ability to modify some of its features proved essential to recovering the mission.

D. Attitude Determination and Control Subsystem Overview

The attitude determination and control subsystem (ADCS) provides three-axis control of the spacecraft. Attitude knowledge is achieved using star trackers, magnetometers and coarse sun sensors. Attitude control is maintained using torque rods, reaction wheels and thrusters.[4]

IV. CloudSat Battery Anomaly

In late 2009, CloudSat's battery started showing initial signs of aging when it suffered a soft-short in one of the cells.[5] Although degraded, battery capacity was sufficient to support CPR collections through eclipse, but it was necessary to restrict ground contacts to the sunlit portion of the orbit. Despite this mitigation, the end-of-discharge voltage level often hovered close to the first under-voltage fault threshold. On 17 April 2011, the first UV level fault was tripped. The team's immediate response was to increase the battery charge level, but despite this adjustment, within 24 hours the satellite descended through the remaining UV levels, causing activation of the Emergency Mode.

A. CloudSat Enters Emergency Mode

Upon entering Emergency Mode, the thrusters were fired to place CloudSat in a stable spin around the X-axis and the solar arrays were rotated to achieve positive power regardless of the spacecraft orientations relative to the Sun. The UV fault was tripped multiple times in the coming week and the associated UV fault response continued to shed all but the essential power bus each time it was tripped, however the thrusters were never fired again.

In this mode, and by design, solar input to the arrays varies, but the spacecraft remains sufficiently power positive so that the battery gets recharged even under the worst-case conditions. This design, however, assumed the battery would have sufficient capacity to support the essential loads, *including* survival heaters. When the survival heaters were on, the battery was unable to meet the demands of even the low-power Emergency mode. Available data indicated the battery was now only able to supply 10% of the energy it had supplied a few days earlier.

Fig 4 illustrates the sinusoidal charging caused by the spinning spacecraft during the sunlit orbit (red line) and the variation in the rate of eclipse battery discharge caused by unstable durations of survival heater loads (green line). Unless a solution was found, it would be impossible for the battery to support any additional loads needed to recover the spacecraft.

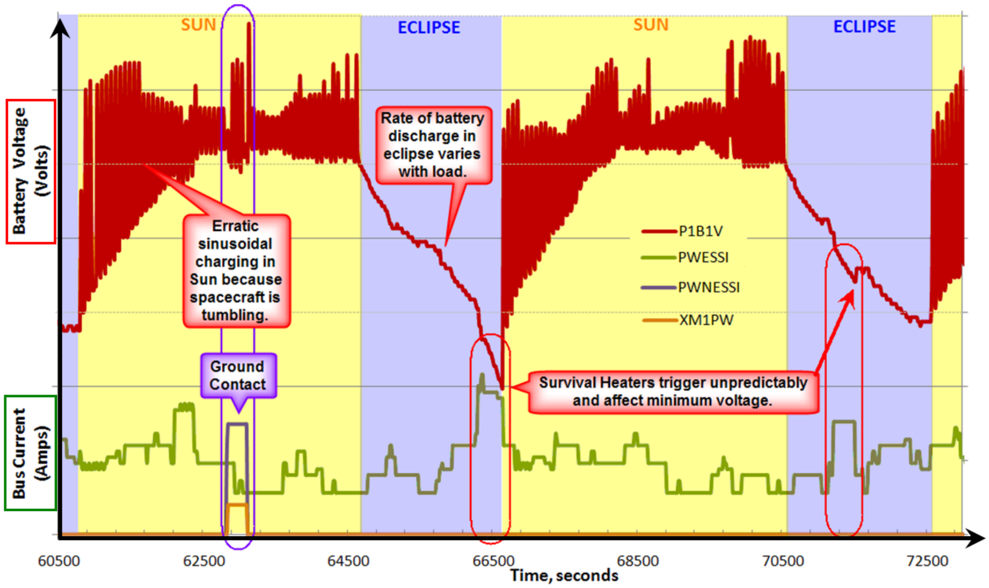

Figure 4. CloudSat Current-Voltage-Time Graph

B. Characterizing the Battery Anomaly

Initially it was believed that the battery had suffered another soft-short. Further analysis determined the battery was suffering from *diffusion-limiting current*, a condition caused by corrosion of the positive electrode which results in the net loss of electrolyte.[10] The reduced amount of electrolyte reduces the ability to support the current demands and there is a sudden drop in voltage when the diffusion-limit is reached.

In the event of a cell experiencing a hard short, CloudSat's design included a spare two-cell common pressure vessel (CPV) that could be switched into the circuit. Unfortunately, this spare CPV could not be used to alleviate the diffusion-limit phenomenon suffered in April 2011, nor the soft-short of December 2009 because in both cases, the voltage of the affected cell indicates it is healthy while being charged, but the voltage quickly drops to full the discharged level shortly after a load is applied. If the spare CPV was connected, it would be necessary to use manual charge control to achieve the voltage level needed to charge the battery with extra cells. Apart from being operationally intensive, adopting this would place the spacecraft at risk of over-voltage damage, so it was decided to use this option only as a last resort.

The actions of the fault protection system further exacerbated this problem. Every time the ground operators increased the charge rate, the survival heater would turn on in eclipse, the current limit would be exceeded, the UV fault would trip, and in response, the charge level would be automatically reduced to the default level. If the battery had been reasonably healthy this would not have been an issue because even at this low rate the battery would have recharged sufficiently to support the loads. However, with the inability to sustain higher load levels, primary heaters were shed, which dropped the temperature of the battery into the survival range. At this temperature, the battery capacity was further reduced, increasing the frequency of UV faults and creating a recursive problem.

The first step to recovery was taken when a method for solving this issue was devised. The key was utilizing the redundant power control system. It provided a number of "knobs" that could be turned to compensate for anomalous behavior, but when operating in the hot back-up configuration, the options available were more limited. The system was therefore divided in half. One half was assigned charge control, with UV protection disabled, while the other half was assigned UV fault protection duties. Originally, the fault thresholds had been set conservatively above the minimum operating voltage of the components to ensure a healthy reserve. In the new configuration, these thresholds were substantially lowered while retaining a higher charge rate. After implementing this change, battery temperature increased to a more comfortable level and the frequency of UV faults was reduced, giving the team breathing room to explore recovery options adaptively instead of reactively.

The next step would be to find a method of managing heater loads in eclipse. But first the matter of CloudSat's potential threat to other on-orbit assets had to be addressed.

C. Exit from the Afternoon Constellation

Several weeks into the recovery it became clear that CloudSat was drifting out of its control box toward AQUA. If CloudSat did not take action, AQUA would be forced to interrupt its nominal operations and

maneuver out of CloudSat's way. The challenge was further complicated by the spin rate. As shown in Fig 5, solar, gravitational, and magnetic torques were causing the original spin rate of Emergency Mode to decrease, further endangering the already delicate power and thermal conditions. The team had to re-establish the stable spin rate by firing thrusters, but this would impart a small ΔV in an unpredictable direction – a potentially dangerous action while still in the A-Train.

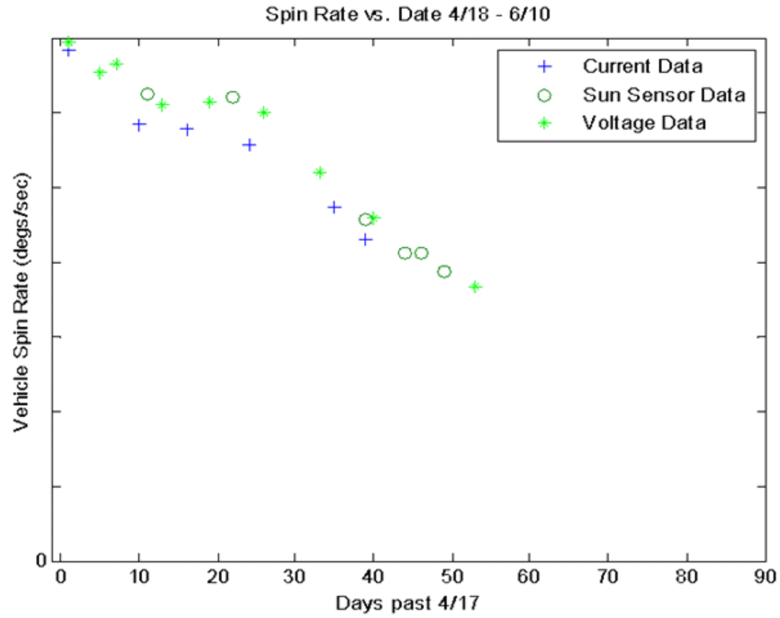

Figure 5. Variation of Emergency Mode spin rate early in the recovery

Other than the battery, all systems on CloudSat were fully functional, so the Project made the decision to attempt to exit the A-Train by lowering CloudSat's orbit. No maneuver would be possible without the Spacecraft Computer (SCC) staying on through eclipse. The team calculated a pre-heating strategy: manually controlled heaters would be used to add heat to critical components during the sunlit portion of the orbit to ensure that the survival heaters did not turn on in eclipse, making it possible to avoid UV faults and keep the SCC on.

CloudSat was in a sun-synchronous polar orbit and would head south-to-north during the sunlit portion of the orbit. At one of the southernmost ground stations, during one 10-minute contact, the USAF/RSC team transmitted all the commands needed to conduct the maneuver sequence to exit the A-Train. After loss-of-signal, the SCC started executing the complex and time-consuming sequence to turn select heaters on, recover control and execute the planned maneuver sequence to exit the A-Train. Components were pre-heated during sunlight, the maneuver sequence executed successfully and the spacecraft returned nominally to Emergency Mode following the maneuver.

D. Halfway There: Escaping Emergency Mode

The success with the pre-heating strategy during the A-Train exit operation pointed the way toward recovering from Emergency Mode. It had been shown that the manually controlled heaters could be used to keep the survival heaters off. With the SCC on, the recovery could progress. It would, however, be necessary to cycle these heaters, as well as nearly every other component, on and off at every eclipse exit and entry, an unsustainably long and arduous commanding task. Fortunately, the spacecraft had a built-in feature that had previously gone unused, which allowed it to store relative-timed sequences of commands that could be executed over and over.

The spacecraft was only able to produce the power need to support the manual heaters in a relatively narrow range of spin-to-sun orientations. Further, all of the existing modes of operation were 3-axis controlled with zero net momentum. Therefore, without the power to keep the reaction wheels on during eclipse, any residual momentum would cause the spacecraft to drift and it was entirely possible the solar array would be off-pointed enough that the power demands would not be met on eclipse exit. Additionally, the spin rate could be adversely affected by environmental torques.

The next step of the recovery was to develop a "new mode" that would hold the spacecraft within this narrow range when it was sunlit and overcome the environmental torques. A further constraint on this new mode was

that it had to point the solar arrays at the sun at eclipse exit so the arrays could immediately supply all of the power needed by the spacecraft without any help from the battery. Finally, this mode could not be achieved by uploading new software – time and expense involved with this approach were cost prohibitive.

E. Sun Point Spin

The initial solution was to develop a controlled spin mode known as Sun Point Spin (SPS), shown in pictorial form in Fig 6. In this mode, the attitude control system uses torque-rods to maintain a constant spin rate, and point the spin axis at the Sun. The solar arrays were left in an orientation to achieve positive power margin. To survive eclipse, the spacecraft was put into a low power hibernate mode, which included turning off the torque-rods. Since the spacecraft was spin stabilized, it maintained the desired orientation while it was in eclipse, and at eclipse exit, the spacecraft could be powered on without fear of over taxing the weakened battery.

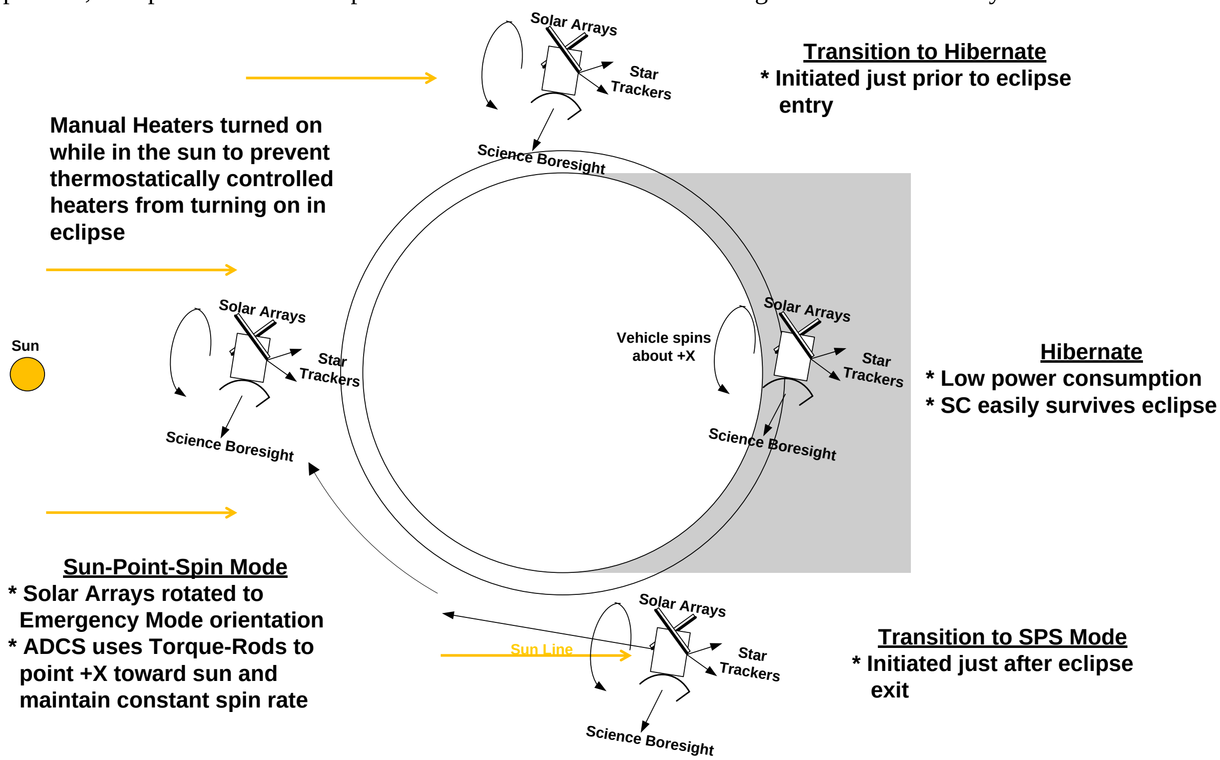

Figure 6. Diagrammatic flow of Sun Point Spin (SPS) Mode

The preliminary trial of SPS, which had the spin axis pointed directly at the Sun, was not totally successful. Increased heater power needs were being imposed – the small cross-section, as viewed by the Sun, was causing the spacecraft to run cooler. This was solved by pointing the spin axis 20 degrees off the Sun, the resultant increase in solar cross-section providing a good compromise between power and thermal needs.

V. CloudSat Recovery to Daylight Only Operations

A. Momentum-Bias Point Mode (Point-Standby)

SPS Mode showed that it was possible to keep the SCC powered and quickly recover operations after exiting eclipse. The team used these lessons to develop the next mode in the evolutional chain, a Momentum Biased Point (MBP) Mode. The principle of MBP was to store momentum in the reaction wheels. When the wheels were turned off, this momentum would be transferred to the body of the spacecraft, causing it to spin up, similar to SPS.

The major constraint on MBP was that the momentum had to be low enough to be stored in the wheels and still meet pointing and maneuver requirements, yet large enough to maintain the proper attitude through eclipse. Additionally, this mode had to be able to flip the spacecraft around so that the orientation at eclipse entry was the same as it was at eclipse exit. This is illustrated in Fig 7. As it turned out, the existing Point-Standby Mode could be modified by changes to flight software (FSW) parameter tables to meet these requirements. Point-Standby

was already designed to do the yaw flip; CloudSat's wheels had been designed with sufficient excess capability to accommodate this mode's obligatory momentum storage.

While it was relatively easy to make this new mode work, it took considerable effort to make it work well. In MBP, the ADCS subsystem stops the spin and maneuvers to point the CPR boresight at nadir shortly after eclipse exit. As the spacecraft flies from south to north, it rotates about the boresight to point the +X-axis in the direction of the Sun while also rotating the solar arrays to point at the Sun. As with all the new modes, the spacecraft was placed into a low-power hibernate mode while in eclipse.

B. Graduating to DO-OP with a Preparatory Mode

With the success of MBP, a return to full operational capability was within easy reach. Daylight Only Operations (DO-OP) mode would only require the addition of CPR on/off cycling to the Point-Standby sequence. There was, however, one issue that had to be resolved first. An important component of CPR science data is geo-location, which enables analysis of specific weather systems across certain areas or comparison with global trends[6-9]. In order to make this possible, both the GPS and the Solid State Recorder (SSR) had to remain active and powered throughout eclipse; however, both were powered by the Payload bus, which had not been turned on during eclipse yet. The loads were small enough for the battery to support through eclipse, but this bus also powered two thermostatically controlled "stability" heaters that could not be disabled. If triggered in eclipse, these heaters would almost certainly trip a UV fault.

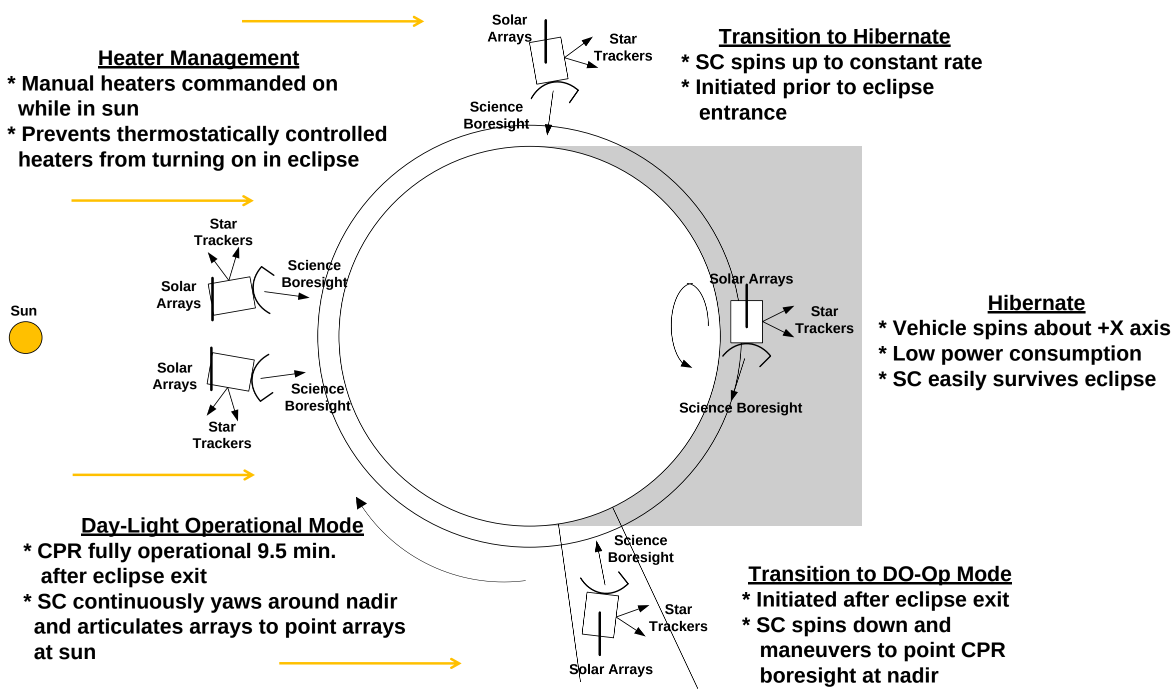

Figure 7. Diagrammatic flow of Standby, Prep and DO-OP Modes

Once again, the team leveraged the lessons learned from previous successes. The pre-heating strategy was re-calculated with the goal of creating extra heat from the manual heaters in sunlight and raising the temperature above the set point of these heaters. The problem was that it would take longer than one orbit to reach this point. The solution was to add a preparatory mode – "PREP" would bring the spacecraft up to a full operational state during the sunlit portion of the orbit, but still keep the payload bus off in eclipse. This sequence would be repeated until the desired temperature was reached, at which point CloudSat could switch to DO-OP mode and be back in the business of gathering cloud science data.

C. Making it an Operational System

Throughout the recovery process, the goal of making CloudSat truly operational once again was never far from mind. The first step toward accomplishing this goal was to adapt the new modes developed during the recovery to provide a layered fault response capability. For example, the system will now autonomously

transition to the new Point-Standby if a UV fault is tripped. A variant of SPS called “Recovery Mode” was developed to respond to attitude rate and pointing errors. Recovery Mode uses less power than SPS Mode. In a poor power orientation, the spacecraft will stay power positive as it autonomously maneuvers to an attitude where the higher power SPS Mode can be engaged.

The ability to conduct ΔV maneuvers was also added. The first maneuvers to be added were two collision avoidance (COLA) sequences, designed to conduct an orbit lower or orbit raise on short notice.

Currently the ability to conduct the ΔV maneuvers to re-enter the A-Train is being tested and implemented. This includes providing the capability to conduct large inclination increase and decrease maneuvers, as well as small trim burns for constellation station-keeping.

Today, DO-OP has evolved into a fully operational flight mode. All the modes have been standardized to allow for easy switches and to reduce the probability of errors in execution. Fig 8 below illustrates the newly designed modes on CloudSat and contrasts them with the old modes at the time of launch.

New Mode	Old Mode	Key Feature
Daylight Only Operations (DO-Op) a.k.a “Momentum Bias Point” Prep	Operational (Point Mode)	-SC is fully operational -CPR taking data -CPR boresight pointed at nadir -SC maneuvers around boresight to point +X axis at sun
Standby a.k.a. “MBP-Standby” or “Point Standby”	Standby (Point-Standby)	-Similar to DO-Op but Payload is off -Spacecraft FSW/ADCS using heritage Point Standby target
Sun-Point-Spin (SPS) Recovery	Acquire Sun	-Spin Rate Controlled -Spin Axis Pointed within 20° of Sun -Solar Array rotate to +/- 40° -CSM and ICV are valid
Spin	No Equivalent Mode	-Spin Rate Controlled -Solar Array rotated to +/- 40° -Used after CPU reset (no CSM / ICV)
Emergency	Emergency	-No Change

Figure 8. Comparison of Old and New CloudSat Flight Modes

D. Evaluation of success of current CONOPS

Once the spacecraft demonstrated it could support operations in the DO-OP mode, the team’s efforts focused on recovering the CPR. The first power-on of the instrument since the anomaly occurred on Sept 28, 2011. Through much of October 2011, the CPR was incrementally powered on, repeating the check-out sequence used post-launch. Once all elements of the CPR were verified to be healthy, it was powered on for successively longer periods of time, until it was consistently operating for 54 minutes each orbit. Following a final adjustment in pointing, the project office at JPL declared CloudSat to be fully operational in November 2011.

Successfully collecting radar data again, CloudSat could now return to its original orbit in the A-Train. Just like all other operations, maneuvers had to be conducted during the sunlit portion of the orbit. This constraint would place consistent challenges on the USAF-led Mission Engineers at the RSC; however, with the anomaly experience gained from the past six months, they were up to the task. The first demonstration of maneuver capability occurred in October 2011, when CloudSat successfully conducted a maneuver to avoid a potential collision with a piece of space debris. With this demonstration of maneuverability, the Project had the confidence to recommend to NASA that CloudSat be allowed to return to the A-Train. A plan for this return is in place and currently executing toward completion.

VI. Lessons Learned from the CloudSat Anomaly Recovery

With the bulk of the anomaly response and recovery complete, our attention now turns to operational lessons learned. Over six months of contingency commanding and frequent setbacks, a lot was learned regarding mission management of an anomalous R&D satellite.

A. Keys to Success

From start to finish, this recovery was a team effort. This section presents some of the team's keys to success, without which CloudSat would not be operational today.

1. **Communication** – Effective communication between a geographically separated team was critical to keeping everyone on the same page. Open teleconferences were conducted for hours at a time. Subsystem engineers were working to understand and characterize the failure, and operators were focused on capturing critical engineering telemetry from the spacecraft to assist in the characterization. Though there were disagreements, things could be easily resolved due to the open lines of communication.
2. **Involvement** – Operations concepts were being developed at BATC, decisions were being made by JPL, and implementation being done by operators at the RSC. All of the organizations (BATC, JPL and RSC) reviewed the plans prior to upload to the spacecraft. An important part to the operators' success was keeping the entire team involved at a technical level. An understanding of the reasons for modified operations or higher importance to certain telemetry values kept everyone knowledgeable and fostered a high degree of collaboration.
3. **Co-Location** – JPL Project Managers and experts were imbedded with the spacecraft team at BATC and the JPL Flight Director was imbedded with the operations team at the RSC. This facilitated face-to-face interaction to ensure smooth communication and rapid decision making. Just as importantly, it fostered a better understanding of the needs and constraints of the different organizations during difficult and often stressful times.
4. **Creativity** – Due to the severity of the battery limitations, engineers at BATC were challenged to come up with a new and innovative ways to operate the spacecraft. The BATC team deserves much credit for conceiving and implementing new approaches to fault protection and momentum management that today allows the spacecraft to reduce loads during eclipse and emerge into the sun with the solar arrays immediately receiving energy. Another example is the ground limitations that stymied the RSC from uploading blocks containing more than 540 commands. Several of the new modes require larger blocks, but once again, creativity reigned. RSC Mission Engineers developed new command management techniques that allowed larger blocks of commands to be uploaded given the same contact duration.
5. **Urgency** – On occasion, due to either RSC problems or antenna restrictions at the ground site, the vehicle has "faded hot", i.e., gone over the horizon with the transmitter on. Rapid response by RSC Mission Operators to realize the error, add up an emergency contact, generate the pass plan and bring up the contact within *minutes* prevented setbacks by eclipse UV faults.
6. **Flexible Assets** –
    - **a. AFSCN**: As an R&D satellite (lower priority than operational satellites), CloudSat was vulnerable to being bumped from scheduled AFSCN contacts. However, when needed, RSC Mission Engineers and Operators were able to successfully lobby for extra contacts and effectively and efficiently responded to the challenges posed by sudden faults, COLA events, and short notice changes in plans. The worldwide reach of the AFSCN assets, together with the flexibility of the staff, were both indispensable to the recovery.
    - **b. Ground System Architecture**: In addition, having a thoroughly designed and vetted ground system that was capable of distributing telemetry and trending data within minutes of a contact was crucial to BATC engineers being able to understand and characterize the spacecraft behavior immediately and prevent degeneration of recovery efforts.
    - **c. Flight Software Test Bench:** The team was generating completely new operating modes. Had a similar situation occurred before launch, the magnitude of changes that were necessary would probably have taken 6-9 months of ground testing alone. The availability of a software test-bench to evaluate and validate performance of the new modes was quintessential. Using this bench also enabled developers at BATC and operators at the RSC to speak the same language and carefully coordinate actions, managing and helping mitigate the risk of game-ending commanding errors.
7. **Veteran Team** – As soon as the anomaly occurred, Project management, with the support of BATC, JPL and USAF management, was able to quickly pull in experienced resources from other areas to assist in the anomaly resolution. This included veteran CloudSat engineers who were familiar with the spacecraft systems and experienced operators who were familiar with the operations.
8. **Risk Management** – Given that the spacecraft was in serious jeopardy, creative engineering solutions were needed, but risk had to be balanced each step of the way. However, by far the biggest risk was indecision: not responding in a timely fashion would have lost the battery altogether due to insufficient charging and

decreasing temperatures. Risk mitigation became a three-step process: Internal team checks, test bench runs and on-orbit validation. There was also a human element to risk management. Care had to be taken to ensure that communication was effective amongst team members and between physical locations: JPL (California), BATC (Colorado) and the RSC (New Mexico). It was also important to appreciate that a tired team can make mistakes, so managing the human factors was also a key to our success.

B. Team Takeaways

Once thought to be on the brink of satellite end of life (EOL)[3], the CloudSat team was able to demonstrate the possibilities of being flexible with re-defining CONOPS in the name of saving a multi-hundred-million dollar mission. It is hoped that our lessons and takeaways may be useful to other mission personnel that find themselves in an analogous situation.

1. **Understanding** – Never give up on trying to understand the problem. Despite many meetings and teleconferences with experts, it took approximately four months to fully understand the anomalous battery behavior and its discharge response during eclipse.
2. **Scrutiny** - CloudSat is now flying and operating in a mode in which it was never intended. This "new normal" continues to challenge the team as they learn nuances about the way the spacecraft behaves in DO-OP. Performing even the simplest maneuvers or implementing the smallest change to onboard sequences can impart un-expected results. The team must continue to scrutinize changes, anticipate unintended results and *test, test, test* prior to implementation. In similar situations, management, engineers and operators alike are all encouraged to "push the alert button" if anything is unclear or uncertain. Resources such as the FSW test-bench are absolutely essential for such efforts.
3. **Risk** – Don't be afraid to accept risk in the face of recovering from a serious anomaly. Often times a decision has to be made despite not having all the desired information. Depending on the situation, inaction can cost a higher price.
4. **Luck** – Don't be too quick to downplay the luck factor, both good and bad. We were lucky that the battery had just enough capacity left to support the DO-OP mode. We were lucky that we didn't lose the spacecraft altogether while we were fighting to regain control in the first few weeks. We were lucky the spacecraft survived during a time of an extended ground system outage at the RSC, leaving us unable to contact it for days. There will always be unknown unknowns and, much as we would like to take complete credit for the successful recovery, luck had a hand to play in it too.
5. **Staffing** – There will always be times that short notice work comes up in anomalous situations. Over an extended timeframe, this could sometimes be a problem. If the situation permitted, the operators requested advanced notice of late work and staggered their shifts to insure coverage. Ultimately this reduced the risk to operations, because building multiple new commands on a daily basis was highly labor intensive and if done wrong, could negate all the good work done to date. Given notice and manning leeway, the RSC team was also able to develop several automated scripts to remove much of this labor and risk.
6. **Mission Assurance -** The team had neither the time nor the resources to conduct extensive reviews. Given the urgency of a degrading situation, such actions can slow if not set back a recovery effort. NASA HQ entrusted JPL and the Project team with the recovery effort, which was a critical enabling factor. More importantly, with that trust comes the responsibility of the operational management to do it right: while several decisions were made on the go at the Project level, independent review teams were brought in at crucial junctures for validation, to include the JPL Office of the Chief Engineer, the JPL Associate Director for Flight Projects & Mission Success and the JPL Office of Safety and Mission Assurance.

VII. Conclusion

In November 2011, NASA/JPL declared CloudSat fully operational in the DO-OP Mode per the revised CONOPS. The spacecraft cycles its subsystems on and off in Sun and eclipse portions of the orbit via weekly command sequences from the RSC. CloudSat is collecting science data during the sunlit portions of the orbit, below the A-Train, and hibernates in a stable spin during eclipse, to recover and return to point at the sun as it emerges from the dark side of the Earth. This new CONOPS requires constant care and monitoring of the thermal and power profiles, as well as more intensive commanding for the CloudSat operators. Though CloudSat will never be a fully nominal mission again, it is collecting data for 54 out of the 65 sunlit minutes in its orbit, and the Cooperative Institute for Research in the Atmosphere (CIRA) has begun distribution of science data to the CloudSat community once again. DO-OP is in use today, and maneuvers are currently being executed to return CloudSat to the A-Train, where it will fly 88 along-track seconds behind CALIPSO and resume its role in the A-Train constellation.

ACKNOWLEDGEMENTS

The authors would like to thank the National Aeronautics and Space Administration (NASA) for funding support that made possible the presentation of this work at the 12th International Space Operations Conference, Stockholm, Sweden. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

There is no substitute for the strong support that was conveyed from NASA to the CloudSat team, including additional funding and the vote of confidence in our ability to recover from the anomaly. We sincerely thank our NASA HQ, JPL, BATC, USAF and RSC management divisions for their support in meeting our resource needs.

But most of all, we thank each and every member of our families during this challenging recovery, for the many long days and nights, missed weekends, missed holidays and family events. We appreciate your sacrifices in helping us achieve success in this passionate challenge.

Appendix A
Acronym List

ADCS	Attitude Determination and Control System
AFSCN	Air Force Satellite Control Network
AIRS	Atmospheric Infrared Sounder
AOS	Acquisition of Signal
BATC	Ball Aerospace Technologies Corporation
CALIPSO	Cloud Aerosol LIDAR & Infrared Pathfinder Satellite Observations
CIRA	Cooperative Institute for Research in the Atmosphere
CNES	Centre National d'Etudes Spatiales
COLA	Collision Avoidance
CONOPS	Concept of Operations
CPR	Cloud Profiling Radar
CPV	Constant Pressure Vessel
CSA	Canadian Space Agency
CSM	Command Storage Memory
CWC	Cloud Water Content
DO-OP	Daylight Only Operations
EOL	End of Life
ESSP	Earth System Sciences Pathfinder
FSW	Flight Software
ICV	Initial Condition Vector
JPL	Jet Propulsion Laboratory
MBP	Momentum Bias Point
MLS	Microwave Limb Sounder
NASA	National Aeronautics and Space Administration
PCU	Power Control Unit
RDA	Risk Decision Authority
RDT&E	Research, Development, Test and Evaluation
RSC	RDT&E Support Complex
SCA	Spacecraft Control Authority
SCC	Spacecraft Computer
SPS	Sun Point Spin
SSR	Solid State Recorder
SST	Sea Surface Temperature
USAF	United States Air Force
UV	Under Voltage
VT	Voltage-temperature (Battery charging algorithm)

References

[1]Goddard Earth Sciences Data and Information Services Center, "GES DISC Google Earth Topic at AGU 2007 Fall Meeting" *GES DISC* [online database], URL: http://disc.sci.gsfc.nasa.gov/gesNews/ges-disc-google-earth-topic-at-agu-2007-fall-meeting [cited 06 March 2012].

[2]H. Su and J. Jiang, 2012, Tropical Clouds and Circulation Changes 1 During the 2006-07 and 2009-10 El Niños, Submitted to Journal of Climate.

[3]Nayak, M.V. "End of Life Procedures for Air Force Missions: CloudSat and TacSat-3". *Proceedings of the 22nd AAS/AIAA Spaceflight Mechanics Meeting*. 22nd AAS/AIAA Spaceflight Mechanics Meeting, Francis Marion, Charleston, SC. *AAS 12-177*.

[4]CloudSat-Calipso Launch Press Kit, 2006, National Aeronautics and Space Administration, URL: http://www.jpl.nasa.gov/news/press_kits/cloudsat-calipso-launch.pdf

[5] NASA Engineering and Safety Center Technical Assessment Report, "Wilkinson Microwave Anisotropy Probe (WMAP) Battery Operations Problem Resolution Team (PRT)", NESC-RP-10-00608, August 5, 2010, URL: http://www.nasa.gov/pdf/475540main_WMAP%20Battery%20Operations%20Problem%20Resolution%20Team.pdf

[6]Cetrone, J., and R. A. Houze, Jr., 2011: Leading and trailing anvil clouds of West African squall lines. J. Atmos. Sci., 68, pp. 1114-1123.

[7]Knippertz, P.; Fink, A. H.; Schuster, R.; Trentmann, J.; Schrage, J. M.; Yorke, C., 2011: Ultra-low clouds over the southern West African monsoon region. Geophys. Res. Lett., 38, L21808, doi: 10.1029/2011GL049278

[8]Luo, Yali; Zhang, Renhe; Qian, Weimiao; Luo, Zhengzhao; Hu, Xin, Intercomparison of deep convection over the Tibetan Plateau-Asian monsoon region and subtropical North America in boreal summer using CloudSat/CALIPSO data, Journal of Climate (0894-8755), April 2011. Vol.24, Iss.8; p.2164-2177.

[9]Nair, Anish Kumar M., Rajeev, K., Sijikumar, S., and Meenu, S.: Characteristics of a persistent pool of inhibited cloudiness and its genesis over the Bay of Bengal associated with the Asian summer monsoon, Ann. Geophys., 29, 1247-1252, DOI: 10.5194/angeo-29-1247-2011, 2011.

[10]L. H. Thaller, M. V. Quinzio, and G.A. To, Electronic Technology Center, Technology Operations, Aerospace Corp., 1998: TR-98(8555)-16, Volume Tolerance Characteristics of a Nickel Hydrogen Cell.